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16. ABSTRACT There are many requirements for dispersion models in the Clean Air Act Amendments of 1977 including prevention of significant deterioration, air quality maintenance plans, and new source permits. The historical perspective of dispersion modeling includes both theoretical and practical developments, rural and urban field studies including tracer studies, plume rise, and urban modeling. Photochemical modeling includes both grid point and trajectory models. Off-the-shelf models include level terrain models for elevated point sources, urban point and area sources, and transportation sources; and complex terrain models for point sources. Models are needed for photochemical pollutants, sulfates, and nitrates; they should treat long range transport, topographic effects, build-up of urban concentrations, and aerodynamic downwash. Emphasis is placed herein upon proper interpretation of vertical temperature structure measurements, and the difficulties in determining the magnitude and locations of the highest and second highest concentrations in a year. Modeling improvements can be expected with representative on-site measurement of input parameters, and improved dispersion parameter schemes which must be verified with appropriate field investigations. Terms related to model evaluation are defined. A primary source of error, in comparing model estimates with monitored air quality, is not including the actual change of wind direction with height which determines elevated plume position. Measures for model evaluation will differ depending upon model use. The paper concludes asking for 1) encouragement of model development; 2) improvement of model inputs through on-site measurements; and 3) detailed field investigations.

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AIR POLLUTION CONTROL ASSOCIATION CRITICAL REVIEWS PROGRAM

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D. Bruce Turner, on assignment to EPA's Environmental Sciences Research Laboratory from the National Oceanic and Atmospheric Administration, will present the seventh in APCA's distinguished Critical Review series at the 1979 Annual Meeting. His topic, "Atmospheric Dispersion Modeling," is basic to a quantitative understanding of how emissions from all sources move in the atmosphere and, of ultimate importance, how this information may be used constructively to achieve and maintain clean air. The decade of the 1970's has witnessed an enormous expansion in the technology of urban diffusion modeling. This represents a significant change from an earlier absorption with stack diffusion; for example, in the third edition of *Air Pollution*, edited by A. C. Stern, the chapter entitled, "Transport and Diffusion of Stack Effluents," contains fifteen literature references out of eighty-three with a publication date of 1971 or later, whereas the companion chapter entitled, "Urban Air Quality Simulation Modeling," contains seventy-one out of ninety-two literature references dated 1971 or later. Whereas these numbers do not represent a good measure of the relative importance of these two topics for air pollution control, they do give an indication of where the frontiers of air pollution meteorology research lie. It is because of these recent rapid advances in the science and technology of air diffusion modeling that the Committee invited Mr. Turner to present his Critical Review topic this year.

Mr. Turner's critical review of atmospheric diffusion modeling is published in its entirety in this issue of the Journal to give those who wish to comment on his presentation at the Critical Review session, Wednesday afternoon, June 27, ample opportunity to become familiar with his thesis and to prepare their own remarks. Commentators will be called to the speaker's stand in the order in which they notify the chairman they wish to speak. All written comments submitted to the chairman on or before July 12 will appear in the September 1979 issue of the Journal.

The Critical Review Committee invites your attendance and comments on the afternoon of June 27. It is expected that there will be ample time for discussion following Mr. Turner's presentation. Room number and starting time will be found in the Annual Meeting Program.

Melvin W. First, Chairman
S-3.2 Special Publications Committee

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JOURNAL ARTICLE

ATMOSPHERIC DISPERSION MODELING
A Critical Review

D. Bruce Turner
U. S. Environmental Protection Agency

There are many requirements for dispersion models in the Clean Air Act Amendments of 1977 including prevention of significant deterioration, air quality maintenance plans, and new source permits. The historical perspective of dispersion modeling includes both theoretical and practical developments, rural and urban field studies including tracer studies, plume rise, and urban modeling. Photochemical modeling includes both grid point and trajectory models. Off-the-shelf models include level terrain models for elevated point sources, urban point and area sources, and transportation sources; and complex terrain models for point sources. Models are needed for photochemical pollutants, sulfates, and nitrates; they should treat long range transport, topographic effects, build-up of urban concentrations, and aerodynamic downwash. Emphasis is placed herein upon proper interpretation of vertical temperature structure measurements, and the difficulties in determining the magnitude and locations of the highest and second highest concentrations in a year. Modeling improvements can be expected with representative on-site measurements of input parameters, and improved dispersion parameter schemes which must be verified with appropriate field investigations. Terms related to model evaluation are defined. A primary source of error, in comparing model estimates with monitored air quality, is not including the actual change of wind direction with height which determines elevated plume position. Measures for model evaluation will differ depending upon model use. The paper concludes asking for 1) encouragement of model development, 2) improvement of model inputs through on-site measurements, and 3) detailed field investigations.

Mr. Turner is presently on assignment from the National Oceanic and Atmospheric Administration, Department of Commerce, to the Meteorology and Assessment Division, Environmental Sciences Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Research Triangle Park, NC 27711.

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We have been wrestling with quantifying the meteorological effects on the dispersion of air pollution sources for more than six decades (since World War I) for point sources, and for approximately two decades (since Frenkiel[1] suggested modeling in Los Angeles and Pooler[2] modeled Nashville) for entire urban areas. We have made considerable progress and have considerable room for more progress in our understanding of the effects of our highly variable atmosphere. The quantification of atmospheric effects has been placed in a framework called dispersion modeling or air quality simulation modeling. Although most environmentalists have been exposed to the concept of dispersion modeling, a definition follows:

A *dispersion model* is a mathematical expression of the effects of the atmosphere upon air pollutants. This includes the effects of advection (transport) and dispersion (including dilution by the wind and dispersal due to turbulence) and may also include considerations of plume rise, wind shear, and chemical and physical transformations (including removal mechanisms). See Figure 1.

Inputs to a model require meteorological data and emissions. Initial conditions of two or three dimensional pollutant concentration distributions are needed by some models. Boundary conditions of meteorology and pollutant concentrations are also needed by some models. A simple boundary condition, that of a single background concentration, is used by some models. Model output consists of estimated pollutant concentrations. These may be for various time periods and may be point estimates or a spatial average.

Dispersion models generally are used to estimate future air quality, but to assess the reliability of a dispersion model it is usually evaluated by applying the model for a past period having historical meteorology, emissions, and measured air quality. How close the calculated estimates come to the measured air quality indicates the performance of the model.

Frequently the inferred accuracy of a model is used instead of the appropriate accuracy which takes into account the known or estimated validity of the input data. This has led to a "credibility gap" between the expectations of the user and the accuracy potential of the model. Model accuracy is difficult to determine since it depends upon both the ability of the model to simulate the physics of the atmosphere and the accuracy of the input information. Most evaluations contain the product of these two effects and therefore the numerical results are dependent on how well the physics can be described and how well the other information is known. Model accuracy must be considered in air pollution control decisions. The costs incurred from decisions made on the basis of dispersion modeling for specific sources should be compared to those incurred using alternative techniques such as rollback emission reduction of all sources.

A number of reviews have been written on the subject of dispersion models. Moses[3] provided an early review and DeMarrais'[4] history includes good coverage of dispersion modeling efforts to 1969. The books by Pasquill[5,6] provide excellent discussions on the foundations upon which many of the presently used models are based. Literature surveys on dispersion modeling have been made by Eschenroeder,[7] Johnson, *et al.*,[8] and Zib.[9] The preprint volumes prepared for four symposia on turbulence, diffusion, and air pollution held by the American Meteorological Society,[10–13] the first of which was co-sponsored by the Air Pollution Control Association (APCA) and also the preprint volume[14] of the Joint Conference on Applications of Air Pollution Meteorology in Salt Lake City jointly sponsored by the AMS and APCA contain numerous papers related to dispersion modeling.

The proceedings of the last eight (no proceedings of the first meeting) of nine international technical meetings on air pollution modeling and its application, sponsored by the North Atlantic Treaty Organization's Committee on the Challenges to Modern Society,[15–22] provide considerable information on modeling in Western Europe, Canada, and the U.S.

A particularly valuable volume related to dispersion modeling is the series of lectures of an AMS workshop held in 1975.[23] The individual chapters in addition to giving quite extensive literature surveys give added insight to the subject of dispersion modeling.

Although a section on photochemical modeling is included in this review, the author cannot be considered an expert in this area and has relied heavily on the published literature. Because of its importance to the urban modeling endeavor, inclusion of photochemical modeling is necessary in any dispersion modeling discussion.

It should also be pointed out at the outset that the subjects of accumulation of modeling knowledge in shoreline or complex terrain environments have not been included here although it is hoped that their importance is adequately stressed herein. Lyons[24] has given a review of shoreline information. Egan[25] has given a review of diffusion in complex terrain; additional literature citations are given in Koch, *et al.*[26]

Two additional areas that should be included in a complete discussion of dispersion modeling, that are omitted here, are long range transport and transformations of pollutants. A recent survey of models useful for long range transport is contained in Nuber, *et al.*[27] Hales[28] has discussed transformations. Since the area of modeling visibility impairment is quite embryonic at this time, the reader is directed to a recent three-volume EPA publication[29] for recent developments. Although important to the national air pollution control effort, the subject of modeling pollution from motor vehicles in the vicinity of roadways is also not reviewed.

Requirements for Dispersion Models

Prior to the passage of the Clean Air Act Amendments (CAAA) in 1977,[30] dispersion modeling was applied at the discretion of the user to perform air quality impact analysis. However, with the passage of the CAAA, the Environmental Protection Agency (EPA) was required to take certain regulatory steps related to the use of air quality simulation models.

Modeling was most specifically addressed in Section 310 calling for the "conduct of a conference on air quality modeling" within six months of the passage of the act and "at least every three years thereafter." Special attention was to be given to the prevention of significant deterioration. A conference on air quality modeling was held in Washington, D.C. on December 14–15, 1977. The deliberations of this meeting focused on comments to the Interim Guideline on Air Quality Models[31] which was subsequently revised and issued in April 1978.[32]

The prevention of significant deterioration (PSD) of air quality is addressed as a separate part of the CAAA, Part C. This part of the act provides for issuance of permits prior to construction of major emitting facilities. It indicates that "the required analysis has been conducted in accordance with regulations" (Section 165) and these regulations "shall specify with reasonable particularity each air quality model or models to be used under specified sets of conditions."

Rules and regulations on PSD were promulgated on June 19, 1978.[33] These specify that "estimates of ambient concentration required shall be based on the applicable air quality models given in the Guidelines on Air Quality Models."[32]

Although not as specific with regard to modeling as the previous referenced sections of the CAAA, there are a number of sections that require analysis of source impact where modeling is likely to be used. Section 108 on implementation plans requires air quality maintenance plans. Such plans require permits and preconstruction review for new or modified stationary sources. Implementation plans may include transportation controls, but indirect source (those attracting mobile sources of pollution) review is only required for federally assisted sources, such as highways, airports or other major indirect sources assisted with federal funds.

There are additional restrictions for proposed sources in nonattainment areas (not meeting the National Ambient Air Quality Standards, NAAQS). Section 171 of the Amendments defines nonattainment areas as areas that exceed standards

as shown by monitoring data or calculated by air quality modeling. This is clarified in the regulations of June 19, 1978[33] which indicate that "if an applicant believes that a model used by EPA has either overpredicted or underpredicted the air quality impact of a source, EPA welcomes the submission of data which will more precisely define the impact of the source. For existing isolated sources, air quality monitoring may be sufficient for this purpose." The permit process for proposed sources in nonattainment areas provided for by Section 173 of CAAA primarily includes considerations of emission including "emission offset" and therefore does not require modeling directly.

Section 126 on Interstate Pollution Abatement provides for written notice to nearby states, prior to commencement of construction, on air pollution impact relating to the significant deterioration of air quality increments or significant contributions to levels in excess of air quality standards. Although not explicitly stated, analyses of air pollution impacts will generally use air quality models to assist in the analysis.

The visibility protection subpart (Section 169A) requires a report to Congress this year that includes recommendations for modeling techniques to determine the extent of visibility impairment caused by man made pollution. Such modeling techniques are anticipated to be vital in determining significant impairment of visibility in Federal Class I areas.

Other aspects of the CAAA which require modeling in an indirect way are determinations needed on the air quality impact effect of New Source Performance Standards, Aircraft Emission Standards, and Emission Standards for Hazardous Pollutants. Dispersion modeling results can also assist in determining whether a fluid model or field study is justified for comparison of stack heights with good engineering practice.

Averaging Times

The Environmental Protection Agency has need for air quality simulation models that will estimate short-term (hours to a day) to long-term (monthly to annual) impact of source configurations, ranging from single sources to entire urban areas, for primary pollutants such as carbon monoxide, sulfur dioxide, lead, and suspended particulate matter, and secondary pollutants such as oxidants, NO_2, and particulate matter formed in the atmosphere, for example, sulfates and nitrates. There is also the need to estimate short-term exposures to toxic spills and long-term (multi-year) exposures to hazardous pollutants.

NAAQS exist in a variety of forms. Sulfur dioxide standards are for annual concentrations, a primary 24-hr standard not to be exceeded more than once per year, and a secondary 3-hr standard not to be exceeded more than once per year. Standards for suspended particulate matter are annual and a maximum 24-hr concentration not to be exceeded more than once per year. Carbon monoxide standards are maximums not to be exceeded more than once per year for two time periods: 1-hr and 8-hr. The ozone standard is a maximum 1-hr concentration not to be exceeded more than once per year. The standard for nonmethane hydrocarbons is a maximum 3-hr not to be exceeded between the hours of 6 to 9 A.M. more than once per year. The standard for nitrogen dioxide is an annual concentration not to be exceeded. Consideration is being given to promulgation of a short-term NO_2 standard. The lead standard is a quarterly concentration not to be exceeded.

Source Types

The types of sources that release the above pollutants are many and varied. Quantities of some pollutants, such as dusts and some hydrocarbons, are released from natural sources. Sulfur dioxide is released from large power stations, flares, a large variety of industrial sources, some mobile sources (principally trains and vessels) and many commercial and residential heating units.

Particulate matter is released from combustion sources; industrial operations such as crushing, grinding, and hauling; and from re-entrainment of material deposited on the ground (fugitive dust). Particulate matter may also form in the atmosphere from gaseous pollutants.

Carbon monoxide is released from motor vehicles, some stationary combustion sources, and aircraft during taxiing and queuing. Nitrogen dioxide results from the conversion of nitric oxide from motor vehicles and stationary combustion sources as well as from aircraft with engines at higher power settings.

Oxidants result from the interactions of sunlight with the oxides of nitrogen and reactive hydrocarbons. Emissions of hydrocarbons and NO come from motor vehicles. NO also comes from stationary combustion sources. Additional hydrocarbons are released from industrial sources, such as refineries and gasoline storage facilities, and also from gasoline service stations, paint manufacturing and use, and clothing dry cleaners.

Lead emissions originate primarily from vehicles burning leaded gasoline, with some additional emissions from industrial facilities.

Toxic and hazardous airborne pollutants can result from leaks, spills, incineration, and industrial sources.

Historical Perspective

Recently DeMarrais[4] has provided "A History of Air Pollution Meteorology through 1969." Although our focus here is on a narrower area—that of dispersion modeling, there is little need to reproduce much of what DeMarrais has presented. Therefore a complete history of dispersion modeling will not be presented here—only highpoints.

Although the obvious influence of meteorology on transport of pollutants was long recognized, research into meteorological influences was intensified at the end and after World War I. The Chemical Defense Establishment was created at Porton, England in 1918. Work by Sutton[34] resulted in Gaussian equations describing atmospheric dispersion and evaluation through field studies of parameters related to dispersion. Estimations of air pollutant concentrations were made throughout the 1940's and 1950's using these equations. Convenient presentations of these methods were given in Sutton,[35] U.S. Weather Bureau,[36] and DeMarrais.[37]

There were many contributions to the theoretical concepts of turbulence and dispersion. The work of Taylor,[38] of considerable significance, was not employed until Hay and Pasquill[39,40] put the theory to practical use using specialized instrumentation.

Based on his own measurements and other recently conducted field studies, Pasquill[41] not only suggested that appropriate on-site measurements should be used to estimate dispersion, but also presented a method that could be used where such measurements were lacking. Rather than emphasize the instrumental methods, many authors adapted and presented the method to be used with available meteorological observations.[42–46]

Prior to this development, Singer and Smith[47] used the trace from a wind vane to define "Brookhaven gustiness classes." These classes were also related to dispersion parameters used in Gaussian dispersion equations. Smith[48] edited a handbook presenting these values.

Without the aid of numerous field investigations, conducted both in open countryside and in urban areas, the proper practical use of dispersion estimates and models could not have proceeded. The open country studies will be mentioned first. Gill and Hewson in Dean and Swain[49] first noted the fumigating plume and maximum concentrations from elevated plumes near hillsides in their study of a large smelter plume. Many studies were conducted by the U. S. Army

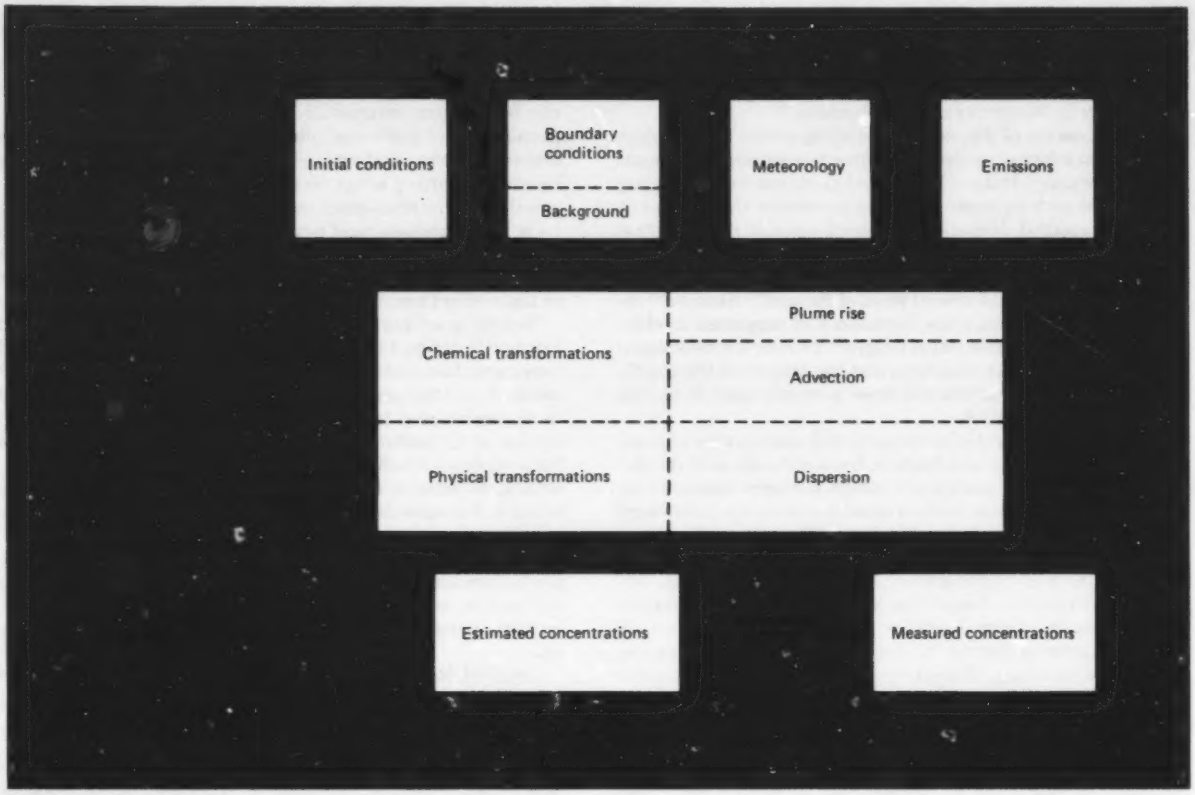

Figure 1. Model elements.

Chemical Corps which contributed to further knowledge of dispersion. Stewart, *et al.*[50] made use of the gases emitted from the atomic pile at Harwell, England as an atmospheric tracer to study dispersion. Gartrell and Carpenter[51] first reported on a long series of quality field studies conducted by the TVA. Lettau and Davidson[52] edited two volumes on the Great Plains study. Hay and Pasquill[39] reported on their experiments relating diffusion to turbulence measurements. Barad[53] edited descriptions and data for Project Prairie Grass.

Diffusion was studied from sampling conducted following two accidents: at Windscale in England reported by Crabtree[54] and in Idaho by Islitzer.[55]

Barad and Fuquay[56] and Fuquay, *et al.*[57] described and gave results of Green Glow experiments using a fluorescent tracer mainly under stable conditions. Haugen and Taylor[58] reported on diffusion programs Ocean Breeze and Dry Gulch conducted in areas with local circulations. Islitzer and Dumbauld[59] also used a fluorescent tracer to study diffusion and deposition out to 3 km. Högstrom[60] used smoke puff photography to examine diffusion over several kilometers. Gartrell, *et al.*[61] tabulated plume sizes from large buoyant sources (TVA) using primarily SO_2 measurements made from instrumented helicopters. Taylor[62] edited a report on a desert diffusion experiment, Project Sand Storm. Smith, *et al.*[63] studied diffusion along shorelines. Carpenter, *et al.*[64] reported on continued TVA studies including plume height compared to plume rise equations. A reasonably complete summary of many of the important field studies is given in Slade.[46] Bowne, *et al.*[65] performed tracer studies in wooded areas reporting enhanced dispersion related to increased roughness. Niemeyer and Schiermeier[66] reported on a study of tall buoyant plumes in irregular mountain ridges.

Of special note is the quality field dispersion work of the NOAA group at Idaho Falls. Early work by this group is included in Slade.[46] More recent studies include Huntington Canyon,[67] Clinch River,[68] low wind inversion conditions,[69] Garfield smelter,[70] Rancho Seca,[71] and additional studies in the vicinity of a reactor building.[72]

Many urban studies also contributed to the knowledge of meteorological influences on pollutants. An early comprehensive study conducted mostly before World War II in Leicester, England was reported by the Department of Scientific and Industrial Research.[73] Trajectory analysis was utilized in interpreting air quality in Los Angeles by Poppendiek, *et al.*[74] Other studies for Los Angeles were reported by Neiburger and Edinger,[75] Faith, *et al.*,[76] and Hamming, *et al.*[77] Halley, *et al.*[78] gave results of a small study in Charleston, West Virginia. Meteorological contributing factors in the Donora incident were discussed by Schrenk, *et al.*,[79] Willett,[80] and Weather Services, Incorporated.[81]

Meteorology associated with a hydrogen sulfide accident in Poza Rica, Mexico was discussed by McCabe and Clayton.[82] Study of the Detroit, Michigan/Windsor, Ontario area was reported by Katz[83] and the International Joint Commission.[84] An analysis of the December 1952 London fog episode was provided by Wilkins.[85] Two studies of air pollution problems in Louisville, Kentucky were reported by Yocom, *et al.*[86] and Public Health Service.[87]

Although most urban investigations were conducted using the pollutants that occurred in the urban areas, tracers were released in a number of investigations specifically to determine characteristics of the dispersion. Studies conducted in three cities in 1953 were reported by Waldron.[88] Interstate transport of tracers was reported by Megonnel.[89] Hilst[90] gives results for an elevated aerial release upwind of Ft. Wayne,

Indiana. A ground-level tracer release study was described by Pooler[91] and results summarized by McElroy.[92] Results of a study using multiple tracers to distances in excess of 100 km were given by Niemeyer and McCormick.[93]

No discussion of dispersion modeling would be complete without an attempt to discuss plume rise estimates. Bosanquet, Carey, and Halton[94] provided guidance for estimating rise but the technique was sufficiently complex that it was not routinely applied. Holland[96] provided a plume rise equation based on data from small to moderate sized sources that has received wide use. Davidson[96] formulated an equation based primarily on the wind tunnel work of Bryant.[97] Stumke[98] reviewed previous plume rise formulas and suggested modifications to fit available data. Briggs[99] provided a new foundation for plume rise equations and has improved the coefficients.[100–103] His equations are those primarily used in models made available by EPA.

Although the effects of moderately tall sources were pointed out,[104–106] the major emphasis in both industry and the developing peaceful uses of atomic energy was upon releases near the ground. Since most of the available dispersion technology was developed for such sources, it was directly applicable.

Although episodes having disastrous consequences had occurred in small communities, Meuse Valley, Belgium, Donora, Pennsylvania, Poza Rica, Mexico, episodes also struck London causing many deaths. Although air pollution control programs were underway in U.S. cities, no dispersion calculations estimating pollutant concentrations in urban areas were made until Pooler[2] made monthly estimates using an emission inventory for 1957–58, made as part of the air pollution study in Nashville, Tennessee. Further details of the Nashville study are contained in Zeidberg, *et al.*,[107] Larsen, *et al.*,[108] Keagy, *et al.*,[109] Stalker and Dickerson,[110,111] and Stalker *et al.*[112] Lack of urban concentration estimates was due to both lack of emission information and lack of facilities to perform thousands of calculations readily. Frenkiel[1] suggested an urban dispersion model and discussed its application to the Los Angeles area, citing the lack of micrometeorological data to determine the turbulence levels. Frenkiel also noted the requirement for high-speed electronic computing machines in order to use urban models practically.

Using the emission inventory of Nashville that Pooler used, Turner[113] applied a short-term model. Clarke[114] provided shortcuts to short-term modeling for estimates at a given receptor. Miller and Holzworth[115] devised an easy method for estimating concentrations at the downwind edge of urban areas and for city-wide means. Martin and Tikvart[116] formulated a long-term (monthly to annual) model that became the AQDM, the first model made widely available. This model was later superseded by CDM[117] and CDMQC.[118] A rapidly executing model based upon the CDM, called the Texas Climatological Model (TCM), was formulated and tested by Christiansen and Porter.[119] A short-term model, the Texas Episodic Model, TEM[120] was also formulated. Bowne[121] produced a detailed short-term model for a large area (Connecticut).

Other urban modeling was done in Jacksonville by Koogler, *et al.*,[122] New York by Davidson[123] and Shieh, *et al.*,[124] Chicago by Roberts, *et al.*,[125] and Bremen, Germany by Fortak.[126] A short cut in calculating concentrations from area sources where emission gradients were not too steep was suggested both by Calder[127] and Hanna[128] using the narrow plume hypothesis. Many contributions to simplifying urban modeling have been made by Gifford and Hanna.[129–133]

An urban model for transportation sources, described by Johnson, *et al.*[134] and Dabberdt, *et al.*,[135] has been made available for wide use. Bringfelt, *et al.*[136] used a model for Stockholm. A finite difference model has been used for St. Louis by Shir and Shieh.[137] A multibox regional model has been applied to the San Francisco Bay area by Knox, *et al.*[138]

Photochemical Modeling

Relatively inert pollutants dispersing in uniform flow fields can be handled successfully with Gaussian modeling by superposition of pollutant plumes. However, pollutants from different sources that react to form secondary pollutants must be modeled using other techniques. Attention has been focused upon the photochemical formation of oxidants resulting from hydrocarbons and oxides of nitrogen. However, it is recognized that consideration of aerosols formed during the photochemical processes are also of importance, especially as to their effect upon visibility.

Several good reviews are available.[7,8,139–141] Ranzieri and Shirley[142] define a photochemical model "as a mathematical representation of air movements and chemical reaction processes that, when combined with emissions and meteorological data, can be used to predict the temporal and spatial distribution of air pollutants." Demerjian[140] lists eight purposes for modeling including research, planning, impact assessment, setting of emission standards, monitoring siting, and episode control. For episode control the models would have to be applied in a forecast mode.

Basically there have been two approaches to deterministic photochemical modeling: 1) the fixed coordinate approach also referred to as Eulerian, grid, and multibox; and 2) the trajectory approach, also referred to as Lagrangian and moving cell.

Seinfeld, Reynolds, and Roth[143] and Lamb and Seinfeld[144] have discussed in depth the assumptions made in applying the continuity equation. Assumptions made include: 1) the pollutant concentrations do not affect the meteorology (temperature and velocity), 2) molecular diffusion is negligible, 3) atmospheric flow is incompressible, 4) the system is isothermal (for convenience), 5) wind velocities and concentrations can be represented by two components: deterministic and stochastic with the average value of the stochastic components equal to zero, 6) turbulent fluxes are linearly related to the gradients of the mean concentrations, and 7) products of concentration fluctuations are negligible. These authors point out the closure problem of having more unknowns than equations.

Lamb and Seinfeld[144] point out that the derived working conservation-of-mass equation is valid for *mean* concentrations provided that 1) spatial and temporal variations of sources are smooth over the integration time step and the travel distance over the time step, 2) the integration time step should be much longer than the Lagrangian time scale of turbulence, and 3) the time scale of the rate controlling reactions are much larger than the Lagrangian time scale of turbulence.

Seinfeld *et al.*[143] and Lamb and Seinfeld[144] point out that the diffusivities for the diffusion equations are determined empirically and accuracy of a given application is highly dependent upon the degree to which the candidate problem corresponds to the conditions under which the diffusivities were measured.

The inputs to the photochemical models include emissions, meteorology, initial conditions, and boundary conditions. Depending upon the model used, emission conditions need to be spatially and temporally accurate. Ranzieri and Shirley[142] and Demerjian[140] give tables of sources and parameters to be included in emission inventories. Roth, *et al.*,[145] give more complete information on emissions.

The spatial density of wind measurement sites is generally much less than desired to specify the wind field. Objective analysis techniques are often relied upon to specify the wind at grid points. In addition to a paucity of surface wind data there are even less data above the ground; many of the models need the wind in three dimensions. Seinfeld[146] indicates that "incorporation of the effects of wind shear and different vertical velocity profiles should really be considered only if there

are sufficient observational data." (It should be noted that many of the Gaussian type models include the increase of wind speed with height.) Objective techniques are available to derive mass consistent wind fields from observations minimizing divergence but preserving vorticity (rotational motion). Minimizing divergence, which causes the vertical winds to approach zero, departs from reality but, if vertical winds are not to be included in the model, allows for the best mass consistent wind fields. For estimates of the magnitudes of errors caused by neglect of wind shear, see Liu and Seinfeld.[147]

The specification of initial conditions requires concentrations throughout the computational volume. Since there is seldom measurement of pollutants in the vertical, specification above ground level is difficult. Effects of initial conditions can be minimized by simulating a long enough period such that all initial parcels of air move away from the region being considered.

Boundary conditions consist of concentrations upwind of the region, pollutant flux (emissions), and flux at the upper vertical boundary. This latter is the most difficult in spite of generally choosing the vertical boundary near the base of an elevated inversion in which vertical transport is at a minimum. Seinfeld[146] points out that it is a special problem to specify initial and boundary conditions in order to exercise a model for hypothetical emission conditions. Ranzieri and Shirley[142] cite some problems and deficiencies in data available for model input.

Demerjian[139,140] illustrates the impact of initial conditions on both grid point and trajectory models. Reduction in initial concentrations by 50% tends to decrease the ozone peak by 20–30% in a grid point model. With a trajectory model, ozone concentrations seemed to change ±20% in response to a ±20% change in initial concentrations. There are numerous methods of numerically solving the diffusion equations. For the grid point model lengthy calculations are needed to integrate several coupled nonlinear equations in three dimensions. Finite-difference schemes are one such method. Seinfeld, *et al.*[143] indicate that the principal considerations in choosing a finite-difference method are accuracy and stability as well as computation time and computer storage. They state, "Accuracy refers to the degree to which the numerically computed temporal and spatial derivatives approximate the true derivatives. Stability considerations place restrictions on the maximum time step that can be used in integration." The main advantage of finite difference methods is the past experience available in applying these techniques to partial differential equations, although there is not much accumulated experience with three-dimensional, time-dependent, nonlinear problems. Disadvantages are: 1) inaccuracies in approximating the advection terms in the continuity equations (this causes second order errors that have the characteristics of diffusion, and hence are referred to as numerical-, artificial-, truncation-, or pseudo-diffusion errors); and 2) excessive computing time and storage requirements. A technique which advects the moments of pollutant distributions instead of the pollutants was devised by Egan and Mahoney[148] to minimize numerical-diffusion. Another method of eliminating numerical-diffusion has been introduced by Christensen and Prahm.[149]

Another method used with grid point models is the particle-in-cell technique. Seinfeld, *et al.*[143] lists advantages as: 1) eliminates artificial diffusion, 2) no stability restrictions on the time step although it must be small enough to represent movement of fluid particles, and 3) particles can be tagged as to origin. The primary disadvantage is computer storage requirements as coordinates of a large number of particles must be retained. Also in simulating chemistry the mass of each pollutant associated with each particle changes with each time step and causes considerable additional computer storage.

Since it is impossible, because of computer storage and running time considerations, to include detailed reactions for the individual hydrocarbons in urban atmospheres, the chemical kinetics have to be generalized without losing the major features of the hydrocarbon/NO oxidation process. This has resulted in lumping hydrocarbons into one or more classes. Demerjian[139] gives a table summarizing the mechanisms of various authors (varying from a seven step mechanism with one class of hydrocarbons to a 39 step mechanism with four hydrocarbon classes). He also presents a 25 step generalized mechanism with three hydrocarbons.

Reaction mechanisms are first tested against chamber studies for initial adequacy and then tested against atmospheric measurements. Errors may be associated with both. Demerjian[139] lists sources of error. He also indicates that reaction rate constants need to be more accurately determined for at least 12 reactions of the generalized mechanism. Ranzieri and Shirley[142] point out the lack of appropriate emission inventories with regard to more than one class of reactive hydrocarbons. This deficiency will need to be overcome. Lamb *et al.*[144] sum up the goal for a proper mechanism, "In short, we seek a mechanism which incorporates a balance between accuracy of prediction and ease of computation." To this goal might be added the desirability for reasonable computer storage requirements.

Johnson, *et al.*[8] and Eschenroeder[7] present simulation results from photochemical models. It should again be emphasized that the models give average concentrations over fairly large spatial dimensions (over areas several kilometers in size) whereas the air quality measurements are at specific points and frequently are responding to steep spatial pollutant gradients. Johnson, *et al.*[8] give results for three models developed under contract to EPA: two trajectory models, a moving well-mixed cell[150] and a Lagrangian column,[151] and a multibox, Eulerian model.[152,153] Using the correlation coefficient and the root mean square error as statistics, results are shown for carbon monoxide (an inert pollutant) and for a photochemical product (oxidant). The difficulty in trying to compare the trajectory and grid point models is noted.

Ranzieri and Shirley,[141] speaking from the users' point of view, cite the many problem areas with existing data bases regarding emissions, meteorology, and air quality. They discuss the difficulties in readying a model for use in different cities, and suggest sensitivity studies be accomplished so that resources for improvement of model input data can be devoted to improving the measurement of the most important parameters. They tabulate the advantages and limitations of trajectory and grid models and outline a plan of application using first a grid model to locate areas of maximum concentration, then a backward trajectory technique to identify areas of responsible emissions. Strategies to alter emissions are then tested using the grid model.

A program for model verification using the Regional Air Pollution Study (RAPS) data collected in St. Louis is outlined by Demerjian.[140,141] Because of delays in accurately estimating emissions, time tables for accomplishing this verification have been delayed.

The necessity to determine a common set of performance standards is pointed out by Eschenroeder.[7] He emphasized that, "The performance indices must be designed with the model applications in mind." With the myriad of model applications and the many possible statistics of performance available, we find ourselves having great difficulty in generalizing on standards of performance, not only regarding photochemical models but all others as well.

Additional research on the Eulerian multibox model called the SAI model has continued and is reported in a series of reports.[154–157]

The development of the LIRAC models is described by MacCracken, *et al.*[158] and a detailed evaluation of the model in the San Francisco Bay area is given by Duewer, *et al.*[159]

Recently Schere and Demerjian[160] have used a newly for-

mulated photochemical kinetic mechanism in a box model which can be solved using coupled ordinary differential equations. The box volume changes temporally with mixing height changes. Emission changes with time are necessary but spatial changes must be ignored. The mechanism uses four classes of hydrocarbons which are presently set as fractions of total hydrocarbons so that the model can be used with current inventories. The Photochemical Box Model (PBM) is designed to simulate the temporal variation of the average air quality within the region. In making comparisons with concentrations averaged over the available air quality stations in St. Louis, it is noted that boundary conditions at the top of the box may be extremely important as the raising of the mixing height to entrain trapped layers of pollutants aloft must be considered. Since data requirements, especially regarding spatial variations, are considerably less for this model, it is expected that the PBM will be a practical tool for photochemical air quality simulations.

Off-the-Shelf Models

In May 1973 six air quality simulation models were placed on a nationwide computer network for execution by users. One year later these six models were also made available from the National Technical Information Service (NTIS) as FORTRAN source codes on magnetic tapes so that users could compile and execute these models on their own computer facilities. This system of programs was called UNAMAP (User's Network for Applied Modeling of Air Pollution) and has been reported on by Turner and Busse.[161] Also, see Appendix. One of the original thoughts behind UNAMAP, and the primary reason for establishing the system on a computer network, was to make programs available for execution (executables), but not to make the source codes available. This was to prevent unauthorized program modification. With the step to make source programs available, this original thought was compromised. However, making the programs available for use on the user's computers was felt necessary for full utilization as it was not possible for many potential users to purchase computer time from an outside facility if they already had use of a computer.

The original six UNAMAP models were APRAC, CDM, HIWAY, PTMAX, PTDIS, and PTMTP. These models are applicable to primary pollutants. Brief abstracts of these models are given in the Appendix. This group of models did not contain a short-term (hours to a day) urban model applicable to point and area sources. The need for such a model for examination of 3-hr and 24-hr SO_2 and particulate concentrations was critical. Also, since all of these models were applicable to level terrain, no model was available for examination of sources in regions of terrain complexities.

In March 1978, five air quality simulation models were added to UNAMAP. These were CDMQC, CRSTER, PAL, Valley, and RAM. These models are also applicable only to primary pollutants. CDMQC provided additional tables of contributions to concentrations from individual sources at each receptor not available from CDM. The Single Source (CRSTER) Model provided a "brute-force" approach to approximation of maximum 24-hour concentrations that occur with a frequency of once per year from single plants with elevated stacks.

PAL provides a framework for simultaneous calculations from point, area, and line sources with consideration of edge effects from area sources. Valley provides for estimation of concentrations for situations where terrain is not level, as is required for the other models. RAM fills the gap for a short-term model for point and area sources in urban areas. Some confusion exists with regard to RAM since some persons or groups have taken RAM and added terrain adjustments without changing its name. The versions of RAM in UNAMAP are for application over level or gently-rolling land surfaces.

It should be noted that all of the current models in UNAMAP are based upon Gaussian plume concepts.

Applicability of Off-the-Shelf Models

To what segment of the spectrum of analysis problems are the off-the-shelf models applicable?

There are six UNAMAP models that are applicable for continuous elevated releases over relatively level open country terrain. This first group includes PTMAX, PTDIS, PTMTP, PAL, CRSTER, and RAMR (the rural version of RAM). The Pasquill-Gifford dispersion parameters most applicable to surface roughness of 0.03 m are used in all of these. The three PT models assume that the wind speed input (or assigned internally in PTMAX) is representative of wind speeds at the point of release. PAL can duplicate computations made with PTMTP, but can additionally utilize an option to increase wind speeds with height according to a stability dependent power law. All four of these models use the buoyancy plume rise methods of Briggs. RAMR performs calculations similarly to PAL, but can simultaneously analyze more point sources and includes momentum rise and stack downwash in the plume rise formulations. All five of these models are for application with meteorological data for relatively short periods of record, generally not exceeding several days. On the other hand, the remaining model in this grouping, CRSTER, is normally applied to an entire year's meteorological data for the primary purpose of estimating once-a-year concentrations. This model is expected to be applied to single plants with moderate to high stacks with receptors some distance from the plant. It, therefore, considers neither the gradual plume rise to final height nor the physical separation of individual stacks. In order to consider more than one plant, a frequency version of RAMR, called RAMFR, can be used also with meteorological data for a year for each model run.

A second grouping of off-the-shelf models is those applicable to urban areas with relatively level terrain. UNAMAP models in this category are CDM, CDMQC, APRAC, and RAM.

CDM is a long-term model applicable to point and area sources in urban areas. Application to monthly, seasonal, and annual or longer periods is appropriate. Stability classes are modified internally (all but the most unstable class are shifted toward unstable by one class) to better represent dispersion in urban environments. Also, initial dispersion of low-level sources can be utilized to represent increased roughness over urban areas. CDM has long been considered as a replacement for the earlier AQDM.[116,162,163] The CDM utilizes the narrow plume hypothesis in determining concentrations from area sources rather than the virtual point source method in the AQDM. The CDMQC based upon the CDM provides for additional output tables allowing the user to determine concentration contributions at each receptor from individual sources. This type of detailed output is similar to output available from AQDM.

APRAC primarily considers emissions from motor vehicles from entire urban areas and performs calculations both for short time periods or for a long period of record such as a year.

RAM is a short-term urban model applicable to point and area sources. A frequency version, RAMF, can be used with a year's meteorological data to identify at specific receptors peak concentrations for specific averaging periods as well as the average concentration over the period of record.

A third grouping of models, applicable to nonlevel terrain, includes Valley and CRSTER. Valley is similar to AQDM for flat terrain analyses, but can also calculate concentrations for receptors on terrain at any elevation. Its primary use is for approximating 24-hr concentrations under adverse meteorological conditions (those causing high concentrations) in complex terrain.

CRSTER (also included in group one above) contains ad-

justment for terrain and can make estimates of concentration for receptors at elevations less than the elevation of the top of the physical stack.

A fourth grouping of models, consisting of those applicable to transportation sources, includes APRAC, HIWAY, and PAL. APRAC, included in the urban models above, is applied to entire urban areas. HIWAY makes calculations for single roadway segments. PAL, mentioned previously, incorporates the methods of the HIWAY model and can thus evaluate multiple roadway segments. Also, since PAL includes slant paths in the vertical, it can be used for estimation of concentrations from take-off and approach paths of aircraft.

Primary Needs for Which There Are No Off-The-Shelf Models

All of the off-the-shelf air quality simulation models made available through UNAMAP are based upon Gaussian modeling assumptions. These models are unable to account for atmospheric reactions and transformations of pollutants in the atmosphere except in very simplistic ways such as exponential loss of a primary pollutant. Therefore, models which consider formation of secondary pollutants and transformation and removal of pollutants are much in need. Any one model may not fulfill the needs in this area. A model is required to simulate the photochemical formation of oxidant on the urban or regional scale. Some of the models that are applicable to oxidant concentrations may also be applicable to the formation of urban aerosols.

A model is required to simulate the transformation of nitric oxide into nitrogen dioxide. Again, the photochemical model for oxidant already includes nitrogen oxides in its chemistry. However, a model is required which deals with a smaller scale problem, that of rapid transformation of NO released from a busy roadway due to background oxidants.

Formation of sulfates and nitrates will be difficult to model since both long range transport and transformation of sulfur oxides and nitrogen oxides are involved. Large point sources and entire urban areas need to be considered as sources.

Simulation of the removal of particulate matter by settling and deposition is another requirement. The treatment of materials released through crushing, hauling, and wind reentrainment is the primary problem area rather than release from vents and stacks where control measures keep the amounts released small.

Estimation of pollutant concentrations in situations of complex terrain is especially difficult if concentrations for the highest and second highest 3-hr or 24-hr periods in a year are required. Answers to unresolved questions as to just what the flow and dispersion are for given situations are paramount where terrain obstructions exist to elevations near or above the plume level. Under unstable conditions elevated pollutant plumes have the tendency to rise over terrain obstructions, although they may pass very near the crest.[70] Under stable conditions, plumes tend to alter their paths to flow around obstructions, and the critical factor that is largely unknown in complicated situations is, how close does the plume centerline come to the terrain feature? The impact of multiple sources such as urban areas in complex mountainous terrain is largely unexamined, and periods of maximum concentration would be expected to occur with light winds and possibly with wind direction shifts that move previously polluted air back over the sources.

Suitable techniques for solving land-water interface problems are also required. Changes in roughness and the vertical thermal structure need to be considered. During mainly spring and summer when bodies of water tend to be colder than warm land surfaces in the daytime, the potential exists for elevated sources in shoreline zones to fumigate for longer than the typical half-hour periods of the break-up of nocturnal radiation inversions.

Periods of light winds cause pollutant build-up in urban areas which if continued long enough cause pollutant episodes. It appears likely that light and variable winds contribute to the occurrence of the maximum 24-hr concentration in urban areas, especially if pollutant releases close to the ground are involved. There is a need to have a model capable of simulating these situations.

Models are also required for estimating concentrations in situations where plumes have the potential to be caught in aerodynamic downwash of buildings. Physical modeling (wind tunnel or water channel) is extremely helpful in study of such problems. Neutral atmospheric conditions are easiest to simulate. Towing tank experiments can be used to simulate stable conditions.

Comments on Present Modeling

The information that Pasquill incorporated into his dispersion scheme, to be used if there are no wind fluctuation data available, was primarily from surface and low level releases. The methodology published by Pasquill[41] and put in slightly different form by Gifford[43] has become a popular method for air pollution analysis of the impact of single sources. In part, because of its ready availability, the method has been applied to taller point sources over the years. Lacking methods as easy to use, the Pasquill-Gifford dispersion estimates have been applied to sources up to nearly 400 m physical height having plume rise in excess of 1000 m. This certainly represents applications beyond the scope of the data used to develop the system, in spite of cautionary remarks of Pasquill.

In a recent report prepared for EPA while serving as a visiting scientist, Pasquill[164] reminds us that to make the best use of Gaussian modeling, specific measurements need to be made that relate closely to dispersion. He reemphasizes the use of the standard deviation of the wind direction angle, σ_θ, determined over 1-hr periods. Pasquill had indicated in his early presentations[41] that direct measurements should be relied upon to make reasonable estimates. However, many air pollution meteorologists rely to a great extent on routine ground level observations made hourly which are designed primarily to serve aviation needs, and which are converted to stability categories through the method of Turner (1964).[113]

Where wind fluctuation measurements are not available, Pasquill suggests as an interim measure the use of statistics calculated from 3-min average winds to define longer term meandering of plumes. This would separate hourly periods of highly persistent winds (transporting a pollutant plume more or less continuously over the same location) from periods with significant meander of wind direction during the hour. These differences are not distinguishable using standard observations. Pasquill, in addition to the above methods for horizontal dispersion, suggests that "for vertical spread there are significant current developments which should be incorporated as soon as an adequate classification and consolidation of the results have been achieved." He recommends that, in the meantime, present Pasquill-Gifford σ_z be used with adjustments for 1) roughness, 2) initial buoyant spread, and 3) urban influences.

Meteorologists supporting the atomic energy industry have made use of on-site meteorological measurements for dispersion estimates. Their concern lies in relatively few high-cost sources, compared to concerns of the air pollution meteorologist who often deals with many low-cost facilities. It was thus possible for the atomic energy facilities to install specialized meteorological instrumentation at a very small percentage of the total project cost of each source. Also, regulations encouraged such measurements. Of primary interest to the atomic energy industry is worst-case meteorology (stable conditions with light wind) for low-level releases. The measurement of vertical temperature structure in the lowest layers[165] is a good indicator of these stable conditions.

If there is a significant contribution by area sources (auto-

mobiles or residential heating) or low level point sources, the same conditions as discussed in the previous paragraph (stable and light winds) will produce build-up of concentrations. However, for elevated point sources in relatively level terrain, either isolated or contributing to an urban problem, worst case conditions are more likely to be light wind, unstable conditions for one to three hours and/or moderate wind, neutral conditions with high wind direction persistence for longer periods such as significant fractions of 24 hours. Such a division is not clear-cut, as unstable conditions may contribute to high 24-hr concentrations and moderate wind persistence to high hourly concentrations.

Under unstable conditions the instantaneous plume alternately is released into large updrafts and regions of downdrafts, causing parts of the plume to occasionally reach ground level close to the stack. Because of the appearance of the instantaneous plume to be in large loops, this condition is called looping. Although the time-averaged plume has large dispersion in the vertical, it is this large dispersion that brings significant concentrations to the ground close to the source before much horizontal dispersion can occur. Even for very tall sources having physical heights of from 200 to 300 m, maximum concentrations under unstable conditions are expected to occur within the first 2 km of the source. Since air quality monitoring stations have typically been located beyond 3 km of such sources, few measurements of the actual close-in (within several kilometers) impact have been made.

Under neutral, moderate wind situations, maximum hourly concentrations are generally lower than those discussed above, and the location of maximum impact is further from the source. However, depending upon the degree of wind direction persistence, the neutral plumes may continually impact the same vicinity for a number of hours and cause higher 24-hr concentrations.

Because of the differing conditions affecting the elevated point source, the meteorological measurements suitable for analysis of the potential problems of a nuclear reactor, that is, a low-level source, are not well suited to assessing the pollution potential of elevated point sources.

Stability has been designated by categories of observed temperature difference between 10 and 60 m. Although this approach identifies the stable conditions important to low level releases, the unstable conditions may be misinterpreted. (See p. 1306 of Hanna, *et al.*[166]) If measurements of vertical wind direction fluctuation representative of the height of released pollutants are not feasible, it is currently thought that combining vertical temperature difference with wind speed for a shallow layer of the atmosphere near the ground (where vertical temperature gradients are strongest) into a bulk Richardson number is a proper expression for inferring vertical dispersion. This is especially useful for distinguishing degrees of instability important for the elevated release. Many people have misinterpreted the use of vertical temperature differences by equating them to vertical dispersion rates without proper regard for the height of measurement. Increase of temperature with height (inversion) at plume levels will indicate damping out of vertical turbulence and decreased vertical dispersion. However, under neutral or unstable conditions, temperature differences with height at significantly elevated plume heights will nearly always indicate about neutral thermal conditions; the temperature difference will not be indicative of the degree of instability. This is why measurements near the ground, as the best indicator of dispersion aloft under neutral and unstable conditions, are recommended. Holzworth[167] states, "The occurrence of superadiabatic lapse rates based at the surface with near neutral above is indicative of rapid vertical diffusion throughout the mixing layer."

Many applications of dispersion models are for the purpose of making estimates of impact and then comparing with air quality standards. Current short-term NAAQS are written to be protective of health and are not to be exceeded more than once a year, for example, the primary 24-hr standards for both SO_2 and particulate matter and the secondary 3-hr standard for SO_2. Attempting to estimate the conditions when a combination of emissions and meteorology will produce the highest or second highest concentration during a year and where that concentration will occur is very difficult.

An approach used in the Single Source Model, CRSTER (See Appendix), is a brute force method of calculating concentrations hour-by-hour at a number of receptors for the entire year to determine the highest and second highest concentrations for various averaging times. This approach assumes that the model is equally applicable for all hours of the year, and seems to work reasonably well for single point sources. Sufficient receptors can be oriented in polar coordinate form so that computation time is not excessive.

However, for two or more sources, determining a limited number of receptor positions likely to receive high concentrations is quite difficult. Attempting to screen the meteorology so that all hours do not have to be calculated, is also difficult. There appear to be no ready solutions to this dilemma, so pointing out these difficulties is all that can be done here. It should be added that at the extremely low frequencies specified by the standards there can be significant year-to-year differences in concentrations.[168]

The Pasquill-Gifford horizontal and vertical dispersion parameters, as typically applied using routine hourly weather observations, are functions of atmospheric stability (but only by discrete classes) and distance from the source. Based upon the recommendations of the Stability Workshop[166] not only is it important to make more pertinent atmospheric measurements in order to improve estimates of atmospheric dispersion, but it is desirable to consider the effects of surface roughness and height of release on the dispersion parameters.

F. B. Smith,[169] (discussion also included in Pasquill[6]) provided graphical methods to define stability continuously rather than in classes, and to include the influence of surface roughness in the determination of the vertical dispersion parameter. The method has not been widely used—perhaps because it is presented in graphical form and many of the dispersion estimates presently made rely heavily upon the use of the computer. Cope[170] has fitted a series of numerically defined surfaces to Smith's results and has programmed computer routines to duplicate Smith's graphical methods.

Briggs[102] proposed two sets of formulas for dispersion parameters based upon the Pasquill stability classes—one set for open country conditions and one set for urban conditions.[171–173] The formulas for open country conditions account for height of release. Gifford[173] in speaking about the open country parameters states, "These are intended primarily for use in calculating ground-level concentrations, in particular the maximum values of these quantities for plumes from elevated stack sources. Consequently these values reflect diffusion data for a higher source at greater downwind distances."

Improving Present Modeling

A significant step in improving dispersion models is to collect and use appropriate on-site measurements. Wind measurements should include average hourly wind speed and direction at a height of 10 m, and standard deviation of horizontal wind fluctuations. The vertical stability parameter is a bulk Richardson number determined from temperature, 10 m wind speed, and a 2 to 10 m temperature difference. In addition the height of the surface boundary layer under unstable conditions and the top of the inversion under stable conditions should be determined.

Following the recommendations of the Stability Workshop,[166] Irwin[174] attempted to include existing theory, observations, tank experiments, and numerical experiments in

the development of a scheme which will include effects of stability, roughness, height of release, and distance from the source. The scheme has since been altered in response to suggestions made during review. Lee, *et al.*[175] made some calculations with an early version of the scheme; they found no clear pattern of differences from using the Pasquill-Gifford dispersion parameters. It is very important, for the proper design of tall sources, so that they are both protective of health and constructed at minimum cost, to verify the accuracy of the basic modeling technique and any simplifications thereof.

Although there have been a number of field dispersion experiments, most have not measured the vertical dispersion directly. The typical pattern of measurements is to have a number of sampling arcs at ground level. At each distance the centerline concentration and the horizontal distribution of concentrations can be approximated. By calculating a horizontal standard deviation or determining crosswind integrated concentrations and taking best estimates of plume height and wind speed, a vertical standard deviation can be approximated. Because of the possible errors in each of the parameter values, there are likely to be large errors in the vertical standard deviation. Irwin has restricted his analysis to the few experiments that measure the vertical profile of concentrations directly. Also a number of the variables necessary to evaluate fully the Irwin method were not measured in past experiments. There is a significant need to plan and execute additional field experiments to improve our ability to estimate dispersion, especially of plumes from the taller sources. In order to do this a significant multi-disciplinary field effort is required. The primary purpose of such a field program would be to determine how effluent released from tall sources disperses compared to lower level releases under a variety of meteorological and surface roughness conditions. Sufficient meteorological measurements should be made using routine measurements and more sophisticated research measurements, so that the atmosphere is adequately characterized.

The practical problems faced daily by those required to do impact analysis often involve the release of hot buoyant plumes from large tall sources; therefore, eventual study of the combined effects of initial dispersion due to conditions of release, buoyant rise and dispersion during the transition, and natural dispersion of the leveled-off plume, is needed. However, initial study can more profitably center on the study of the dispersion alone. Therefore, release of a nonbuoyant tracer and sampling downwind is required. The major reason that the required experiments have not already been performed has been the unavailability of funds.

Because it is desirable to examine the differences in dispersion taking place from releases at different heights, and it is difficult to reproduce meteorological conditions at a later point in time, it would be best if two or more different nonreactive, gaseous tracers could be released at different altitudes above ground. Release heights from near ground level to 500 m should be included. Current standards place emphasis on averaging times of 1 hr and 8 hr for CO, 24 hr for SO_2 and particulate matter, with a secondary standard at 3 hr for SO_2. It is generally agreed that an averaging time of 1 hr is reasonable for making dispersion estimates. This insures that only small changes in meteorological conditions take place over the averaging period. Therefore, release of tracer in excess of 1-hr periods with 1-hr sampling is appropriate. Sampling should be conducted in the horizontal and vertical at enough locations to characterize the time-averaged plumes for the 1-hr averaging time. The sampling in the vertical is the most difficult and although remote sampling methods may be feasible, it may not be possible to sample two tracers remotely. (Although aircraft sampling has been used in some dispersion studies it has the disadvantage of being discontinuous in time, making it impossible to determine accurately hourly average concentrations at discrete points.) Meteorological conditions from extremely unstable to neutral are of greatest interest over relatively flat terrain. Tracer sampling to at least 10 km from the source is of interest.

Meteorological measurements in support of these field measurements should include cloud cover and ceiling height to use with stability classification methods. It is necessary to have vertical profiles of the three wind components along with their second and third moments and temperature through the plume depth. The mixing height under neutral and unstable conditions, and the top of the surface based inversion under stable conditions is also required. Temperature difference between approximately 2 to 10 m and wind fluctuation measurements at a 10 m height and at the height of plume release are required.

This suggested field program needs to be conducted at several sites (perhaps three) representing different surface roughness. The purpose of the above suggested program is to measure directly the dispersion under a variety of meteorological conditions from releases at different heights above ground over uniform terrain having several different surface roughnesses. These data could then be used to compare with various schemes of estimating dispersion and short cut methods derived from them.

EPRI, the Electric Power Research Institute has held a workshop to plan some field dispersion studies.[176] Their goal is to examine elevated buoyant plumes. As indicated above there is also the need to separate the effects of natural dispersion and buoyancy in order to gain a more complete understanding of dispersion.

Evaluation of Models

There has been considerable confusion among modelers and users concerning proper evaluation of models and in the terms used. Many modelers consider a careful comparison of estimated pollutant concentrations with measured concentrations to constitute a validation of the model. Johnson[177] and Calder[178] have disagreed with this concept and consider a proper validation to consist of evaluation of each model submodule.

The author has attempted to discuss and arrive at definitions of terms used in evaluation of models that are consistent with normal dictionary usage.[179,180]

Verification, which means the act or process to establish the truth, accuracy, or reality of, seems to be a good term to use to indicate that some sort of mathematical analysis was performed upon a set of data, usually consisting of measured air quality and modeled estimates for the same locations and times, and that the results were favorable. Validation means an act, process, or instance of validating. Validate means to confirm the validity of, to substantiate. Valid means well grounded, having a conclusion correctly derived from premises, sound. Valid and sound mean having such force as to compel acceptance. Valid implies being supported by objective truth or generally accepted authority. Sound implies being based on flawless reasoning and on solid grounds. Substantiate implies the offering of evidence that sustains the contention. Although validation does not have much difference in meaning from verification the definition seems to indicate that the evidence for truthfulness may be somewhat more dominant for validation; thus validation might best be reserved for use such as a second verification that substantiates a previous verification.

> *Verification*—to establish the truth, accuracy, or reality of—implies that a mathematical analysis was performed on a data set (usually consisting of measured air quality and modeled estimates for the same locations and times) with favorable results.
>
> *Validation*—confirmed and accepted—a second verification that substantiates the first one.

It should be pointed out that merely stating that a model

is validated is not sufficient as many different comparison procedures may be applied in verifying and validating models. These will vary primarily for the particular expected use of a model. For example, the same air quality dispersion model may be used, on the one hand, to estimate 3-hr SO_2 concentrations to compare with the secondary air quality standard, and on the other hand, to estimate quarterly concentrations to compare with the lead standard. For the first use, highest and second highest concentrations at each receptor for the 3-hr averaging period would need to be compared. For the second use, 3-month concentrations would be of interest. Therefore, a statement regarding validation should include information as to what statistic or statistics were examined and the nature of the data base.

Although a comparison between model estimates and measurements may verify a model, a good result may be due to compensating errors in various portions of the model. Therefore, to have confidence in an air quality simulation model, verification of the individual portions of the model independently is highly desirable. No special name is attached to this, so this may best be termed: verification by parts.

> *Verification by parts*—to verify individual portions of a model independently.

Evaluate means to examine and judge, to appraise carefully. It appears to be a term with general meaning but does imply judgment. Therefore, an evaluation may best be based upon a verification and subsequent validation but could also be made from an examination of the modules making up the model and the past experience of the worth of these elements.

> *Evaluate*—to examine and judge, to appraise carefully (a general term)—the evaluation may be based upon a verification and subsequent validation *or* from an examination of the model modules and past experience on the worth of those modules.

Accuracy and Precision are terms frequently confused. A mean of some estimates is *accurate* if it has little deviation from the mean of the comparable set of measurements. Estimates are *precise* if there is little scatter for a number of comparisons between model estimates and measurements for the same conditions, such as meteorological conditions.

Comparison has been used previously in this section. Comparison may be subjective such as display of a scatter plot between model estimates and measurements. It can also be quantitative such as deriving various statistics from data sets of model estimates and measurements. Comparisons can be made between model estimates and measurements and can also be made between one model and another using one or more calculated statistics.

> *Comparison*—an examination of two or more items to establish similarities and dissimilarities.

Performance Evaluation is a term sometimes used with modeling and implies that comparisons have been made with a variety of partitioning of the data so that the performance of the model has been determined for a variety of conditions, such as, different meteorological conditions.

> *Performance Evaluation*—determining the performance of a model for different conditions through a partitioning of the data.

Sensitivity Testing is another term used with modeling. This usually refers to determining the change in model estimates as a result of a change in the value of an input parameter. Sensitivity testing is done without any air quality measurements for comparison.

> *Sensitivity Testing*—determining the changes in model output due to specific changes in an input parameter (or parameters).

Occasionally, in the past, modelers and users have used air quality measurements to adjust model output. This has generally been accomplished by comparison of model estimates with measurements by determining a linear least-squares regression line of best fit through the data and then using the equation of this line to adjust model output. This has been termed calibration.

> *Calibrate*—an objective adjustment (such as least-squares linear regression with measured data) to model output so that the mean of the estimates equal the mean of the measurements—the removal of bias of the mean.

Calibration procedures are not recommended for the following reasons: 1) If model output differs from measurements sufficiently to require adjustment, either the input data are insufficient or the model is incorrect or not applicable. The input data should be checked. Improvements may be needed in the model or another model used instead. 2) On the order of 20 to 30 data pairs are required to have statistical significance of a regression line. 3) Outliers (points far away from the regression line) may be very significant. Large overestimates or underestimates at a given receptor point may be due to errors in the emission rates or stack characteristics (affecting the plume rise estimate) of nearby sources. Calibration is not frequently warranted. A calibrated model reduces the bias (over or underestimates of the mean) between the model and the data to random error. This means the calibrated model is technically only valid for this site and data base.

Sources of Errors in Models

The discussion here will primarily be limited to the Gaussian type models applied to relatively inert pollutants.

How well a model represents the true physics of the atmosphere is certainly a source of error. The characterization by only a single stability condition with its related dispersion rate is an oversimplification. Also the assumptions of complete eddy reflection at the ground and the top of the mixing height are oversimplified. The treatment of plumes in the vicinity of the mixing height is not well represented. Current practice considers: 1) a plume whose centerline is below the mixing height to be entirely contained in the mixed layer, and calculations made assume complete eddy reflection, and 2) a plume whose centerline is above the mixing height to be entirely contained in the stable layer aloft and contributes no pollution to ground level. Actually, plumes in the vicinity of the mixing height, above and below, will have a portion of the plume mixing in the unstable or neutral layer and a portion of the plume stabilized in the inversion layer aloft. The representation of the vertical distribution of time-averaged plumes to be Gaussian though modified at the ground and at the mixing height is highly idealized.

Certainly the errors in the input parameter values contribute directly to modeling errors. Considering errors in emission inventory information, source coordinates, physical source height, and diameters are generally well known although errors in coding, etc. can cause sources to be positioned tens of kilometers from their real position. In short-term models the proper representation of emission rate temporal variations can be of considerable significance. Variations in heating content and sulfur content (for SO_2) of fuel can cause significant emission variations. In addition to emission effects, variations in rate of fuel burned will also affect stack gas volume flows significantly affecting plume rise. In long term

models the positive correlations of average emissions with meteorological conditions may bias the resulting computations. For example, space heating requirements in winter will be associated primarily with the stable (nighttime) times of day. Electrical requirements for air conditioning peaks will typically occur in mid or late afternoon near the time of the most unstable conditions.

Errors in meteorological data will also greatly affect concentration computations. Wind speed at stack top is frequently approximated from a low level wind speed at a height of from 7 to 10 m, by using a power law increase in wind speed with height. Although reasonably correct over a long period of record, individual hours may be grossly in error. Wind speed is used both for dilution and estimation of plume rise. These two uses of wind speed tend to work against each other causing resulting concentrations to be less sensitive to wind speed errors. For example, although a decrease in wind speed will cause less dilution tending to increase plume centerline concentrations, it will also increase plume rise tending to reduce ground-level concentrations. Although changes in wind speed do not greatly change the magnitude of the maximum ground-level concentrations, the location of the maximum will shift closer to the source as wind speed increases. Wind speed variations over an hour also serve to cause the plume height to vary having the effect of increased vertical dispersion over the period.

One of the most significant errors in the meteorological data is that the input wind direction is not the actual direction of plume transport. This is generally the case since wind direction changes with height. Usually the available measurements are very near the ground. If the direction of plume transport is not known, the location of high concentrations can not be determined. For regulatory purposes the magnitude of the high concentrations is of importance but its exact location is of little concern. However, the exact direction of plume transport is significant in trying to compare short term model estimates with measurements; or, if one is attempting to estimate a plume position in relation to some elevated topographic obstruction.

Although the effect of the ground's surface friction is such as to cause change of wind direction with height in a clockwise direction, the influence of the horizontal temperature structure (thermal wind) may be such as to overcome the effect of friction and cause a counterclockwise turning with height. Therefore no assumed standard change of wind direction with height is suitable. In most applications the change of wind direction with height is not modeled. At the present, attempting to estimate winds at an elevated plume height is not an easy task. Radiosoundings by free balloon are made twice daily from approximately 60 to 80 locations in the 48 contiguous states. Therefore, in order to estimate hourly winds for an elevated source, interpolation must be made not only in horizontal space and time, but vertically as well, as the resolution in the vertical is averaged over several hundred meters.

The hope for improvement here is the possibility of indirect sounding of the atmosphere. This should be nearly continuous in time. Although using such observations would still require spatial interpolation, if practical sounding equipment can be made cheaply enough, wind measurement systems capable of measuring the wind at both source height and plume transport height might be obtained for use at the sites of existing or proposed sources.

Variability in wind direction due to low frequency meander over the hour contributes to horizontal spreading of the plume. Use of the standard deviation of horizontal wind direction fluctuations from on-site measurements incorporates the effects of this meander.

In the past frequent use has been made of the Pasquill[41] stability classification, relating both horizontal and vertical dispersion to the stability class. Instead, use of on-site measurements are recommended with separate parameters employed for inferring horizontal and vertical dispersion.

Model Evaluations and Comparisons

A number of model estimates have been compared with measurements. Eschenroeder[7] summarizes some of the intercomparisons of models including photochemical models. In the discussion that follows, the statistics used to compare model performance will be emphasized.

Correlation coefficients have frequently been singled out as a statistic of model performance. Gifford and Hanna[133] compared their simple model against other models using the correlation coefficient.

Turner, *et al.*[181] compared two long-term models with a number of other more simple modeling techniques. The means of the measurements and estimates were compared as well as the root mean square error with the standard deviation of the measurements. Also the mean absolute error was tabulated. The largest positive and largest negative errors were examined. An interesting comparison was the maximum estimated concentration at any measurement point compared to the maximum measured concentration. This would be of considerable interest if the intended use of the model is for regulatory purposes. This study also gave correlation coefficients and slope and intercept of the least-squares regression line.

A particularly interesting comparison of models was done by Nappo.[182] Also included were computer time and costs for the various models. Both temporal and spatial correlation coefficients were determined and averaged. The ratio of predicted to observed plus the average and standard deviation of this ratio are statistics used in this comparison.

Koch and Thayer[183] made comparisons of both short-term (1- and 2-hr) concentrations and long-term (1- and 3-month) concentrations from a Gaussian plume model. Numerous comparisons were made including statistics using correlation coefficients and root mean square errors. A later study by Koch and Fisher[184] compared four different models using the same statistics as used by Turner, *et al.*[181]

Comparison of frequency distributions of measured concentrations and estimates made with the CRSTER model were emphasized by Mills and Record[185] and Mills and Stern.[186]

Guzewich and Pringle[187] used primarily correlation coefficients in their evaluation of PTMTP although data were partitioned by stability class to determine performance for each class.

A study of the performance of variations of the CDM in Copenhagen was made by Prahm and Christensen[188] using correlation coefficients.

Burt and Slater[189] compared maximum estimated and measured concentrations directly in an evaluation of the Valley model.

A comparison of calculated and measured ozone in Denver by Anderson, *et al.*[190] compared the percentage of estimates within expected instrumental error of measured concentrations.

Studies of the LIRAC model by MacCracken, *et al.*[191] and MacCracken and Sauter[192] used both temporal and spatial correlation coefficients similar to those used by Nappo.[182]

Many techniques including graphical techniques such as scatter plots, time traces, and frequency distributions were used by Shir and Shieh[137] in evaluating a numerical grid model. Correlation coefficients were also used.

A practical demonstration of urban air quality simulation

models, comparing models of many nations, using a data base for Frankfurt, Germany has been completed under the auspices of NATO/CCMS but is yet to be published.

Evaluation of models is especially difficult for models whose estimated concentrations are compared with short-term ambient air quality standards (concentrations not to be exceeded more than once a year). Tests of model performance for the situations causing extreme concentrations must be conducted. Although a model may perform well for a large majority of conditions, it must not be assumed that it also performs well for extreme situations. This performance must be demonstrated. This becomes difficult since lengthy periods of record must be considered with additional problems of missing air quality monitoring data.

Conclusion

The passage of the Clean Air Act Amendments in August 1977 has placed additional emphasis on air quality simulation modeling as an aid to assessing air quality impact. A number of model developers feel that the specification of particular dispersion models in the Guideline on Air Quality Models[32] will tend to discourage the development of new models. There is the need for improvement of models and for additional models for application to situations for which no models exist. We, therefore need to encourage model development and improvement.

There is so much activity in air quality simulation modeling that it will continue to be difficult to review new models adequately. We must provide for adequate and timely peer review of models and rapid dissemination for application. This must include periodic revision of the modeling guidelines and replacement of techniques with improved ones.

We must strive toward improvement of model inputs. For some types of modeling applications, this area is one where we can expect the most improvement in model performance for dollar expended. Too long have we continued to use standard weather observations where more detailed on-site measurements are required for an adequate understanding of the situation.

We must be willing to expend the resources required to conduct appropriate field investigations for model verification by parts and model improvement. Recent plans by EPRI[176] are steps in the proper direction. Commitment of resources must be commensurate with at least a small fraction of the magnitude of the costs incurred by the decisions based upon modeling results.

Performance criteria for various model uses are required and need to be developed so that better "metersticks" are available for model assessment.

Finally, we need to continue model evaluation by collection and critical assessment of all model comparisons with measured air quality.

Although the future may hold great prospects for solar heating, solar power, and wind power, current inflation rates, energy shortages, balance of payment problems, and a commitment to increased usage of coal, indicate that environmental concerns must be considered along with other problems. Dispersion model improvement and judicious use should help us strive toward a clean environment at the lowest possible price and with the least possible infringement upon the quality of life.

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APPENDIX

User's Network for Applied Modeling of Air Pollution (UNAMAP)

Air quality dispersion models are made available by the Environmental Applications Branch. In addition to having executable programs on EPA's UNIVAC 1110 at Research Triangle Park, NC, a tape having FORTRAN source programs has been placed with NTIS (National Technical Information Service). U. S. Department of Commerce, Springfield, VA 22161. The current tape is called: UNAMAP (Version 3). Its accession number is PB-277-193. There are eleven dispersion models contained on the tape. Brief abstracts and references for each model follow:

APRAC Stanford Research Institute's urban carbon monoxide model. Computes hourly averages for any urban location. Requires an extensive traffic inventory for the city of interest. Requirements and technical details are documented in:

User's Manual for the APRAC-1A Urban Diffusion Model Computer Program (NTIS accession number PB 213-091).

Additional information is available on APRAC from:

A Practical, Multipurpose Urban Diffusion Model for Carbon Monoxide (NTIS accession number PB 196-003).

Field Study for Initial Evaluation of an Urban Diffusion Model for Carbon Monoxide (NTIS accession number PB 203-469).

Evaluation of the APRAC-1A Urban Diffusion Model for Carbon Monoxide (NTIS accession number PB 210-813.)

Walter F. Dabberdt, F. L. Ludwig, and Warren B. Johnson, Jr., "Validation and applications of an urban diffusion model for vehicular pollutants," *Atmos. Environ.* **7:** 603 (1973).

W. B. Johnson, F. L. Ludwig, W. F. Dabberdt, and R. J. Allen, "An urban diffusion simulation model for carbon monoxide," *J. Air Poll. Control Assoc.* **23:** 490 (1973).

CDM The Climatological Dispersion Model determines long term (seasonal or annual) quasi-stable pollutant concentrations at any ground level receptor using average emission rates from point and area sources and a joint frequency distribution of wind direction, wind speed, and stability for the same period.

A. D. Busse and J. R. Zimmerman, "User's Guide for the Climatological Dispersion Model," U.S. Environmental Protection Agency, Research Triangle Park, NC, Environmental Monitoring Series, EPA-R4-73-024, 1973 (NTIS accession number PB 227-346).

HIWAY Computes the hourly concentrations of nonreactive pollutants downwind of roadways. It is applicable for uniform wind conditions and level terrain. Although best suited for at-grade highways, it can also be applied to depressed highways (cut sections).

J. R. Zimmerman and R. S. Thompson, "User's Guide for HIWAY: A Highway Air Pollution

Model," U.S. Environmental Protection Agency, Research Triangle Park, NC. Environmental Monitoring Series, EPA-650/4-74-008, 1975 (NTIS accession number PB 239-944).

Three Point Source Models The three following point source models use Briggs plume rise methods and Pasquill-Gifford dispersion methods as given in EPA's AP-26, "Workbook of Atmospheric Dispersion Estimates," to estimate hourly concentrations for stable pollutants.

PTMAX Performs an analysis of the maximum short-term concentrations from a single point source as a function of stability and wind speed. The final plume height is used for each computation.

PTDIS Estimates short-term concentrations directly downwind of a point source at distances specified by the user. The effect of limiting vertical dispersion by a mixing height can be included and gradual plume rise to the point of final rise is also considered. An option allows the calculation of isopleth half-widths for specific concentrations at each downwind distance.

PTMTP Estimates for a number of arbitrarily located receptor points at or above ground-level, the concentration from a number of point sources. Plume rise is determined for each source. Downwind and crosswind distances are determined for each source-receptor pair. Concentrations at a receptor from various sources are assumed additive. Hourly meteorological data are used; both hourly concentrations and averages over any averaging time from one to 24 hr can be obtained.

D. B. Turner and A. D. Busse, "Users' Guide to the Interactive Versions of Three Point Source Dispersion Programs: PTMAX, PTDIS, and PTMTP." Preliminary Draft, Meteorology Laboratory, U.S. Environmental Protection Agency, Research Triangle Park, NC, 1973.

CDMQC This algorithm is the Climatological Dispersion Model (CDM) altered to provide implementation: of calibration, of individual point and area source contribution lists, and of averaging time transformations. The basic algorithms to calculate pollutant concentrations used in the CDM have not been modified, and results obtained using CDM may be reproduced using the CDMQC.

Kenneth L. Brubaker, Polly Brown, and Richard R. Cirillo, Addendum to User's Guide for Climatological Dispersion Model. Prepared by Argonne National Laboratory for the U.S. Environmental Protection Agency, Research Triangle Park, NC, EPA-450/3-77-015, 1977 (NTIS accession number PB 274-040).

CRSTER This algorithm estimates ground-level concentrations resulting from up to 19 colocated elevated stack emissions for an entire year and prints out the highest and second-highest 1-hr, 3-hr, and 24-hr concentrations as well as the annual mean concentrations at a set of 180 receptors (5 distances by 36 azimuths). The algorithm is based on a modified form of the steady-state Gaussian plume equation which uses empirical dispersion coefficients and includes adjustments for plume rise and limited mixing. Terrain adjustments are made as long as the surrounding terrain is physically lower than the lowest stack height input. Pollutant concentrations for each averaging time are computed for discrete, non-overlapping time periods (no running averages are computed) using measured hourly values of wind speed and direction, and estimated hourly values of atmospheric stability and mixing height.

Monitoring and Data Analysis Division, User's Manual for Single-Source (CRSTER) Model. U.S. Environmental Protection Agency. Research Triangle Park, NC. EPA-450/2-77-013, 1977 (NTIS accession number PB 271-360).

PAL Point, Area, Line source algorithm. This short-term Gaussian steady-state algorithm estimates concentrations of stable pollutants from point, area, and line sources. Computations from area sources include effects of the edge of the source. Line source computations can include effects from a variable emission rate along the source. The algorithm is not intended for application to entire urban areas but for smaller scale analysis of such sources as shopping centers, airports, and single plants. Hourly concentrations are estimated and average concentrations from 1 hour to 24 hours can be obtained.

William B. Petersen, User's Guide for PAL—A Gaussian-Plume Algorithm for Point, Area, and Line Sources. U.S. Environmental Protection Agency, Research Triangle Park, N.C., Environmental Monitoring Series EPA-600/4-78-013, 1978 (NTIS accession number PB 281-306).

Valley This algorithm is a steady-state, univariate Gaussian plume dispersion algorithm designed for estimating either 24-hr or annual concentrations resulting from emissions from up to 50 (total) point and area sources. Calculations of ground-level pollutant concentrations are made for each frequency designed in an array defined by six stabilities, 16 wind directions, and six wind speeds for 112 program-designed receptor sites on a radial grid of variable scale. Empirical dispersion coefficients are used and includes adjustments for plume rise and limited mixing. Plume height is adjusted according to terrain elevations and stability classes.

Edward W. Burt, "Valley Model User's Guide," U.S. Environmental Protection Agency, Research Triangle Park, NC, EPA-450/2-77-018, 1977 (NTIS accession number PB 274-054).

RAM Gaussian-Plume Multiple-Source Air Quality Algorithm. This short-term gaussian steady-state algorithm estimates concentrations of stable pollutants from urban point and area sources. Hourly meteorological data are used. Hourly concentrations and averages over a number of hours can be estimated. Briggs plume rise is used. Pasquill-Gifford dispersion equations with dispersion parameters thought to be valid for urban areas are used. Concentrations from area sources are determined using the method of Hanna, that is, sources directly upwind are considered representative of area source emissions affecting the receptor. Special features include determination of receptor locations downwind of significant sources and determination of locations of uniformly spaced receptors to ensure good area coverage with a minimum number of receptors.

D. Bruce Turner and Joan Hrenko Novak, "User's Guide for RAM," U.S. Environmental Protection Agency. Research Triangle Park, NC, EPA-600/8-78-016, November 1978.